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Research Article

Spatial models of rice fields change and sustainable agriculture in Solok District, West Sumatra Province

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Abstract

Indonesia is an agricultural country and one of the world's rice-producing countries. However, the increase in population has pushed for the conversion of agricultural land to non-agricultural purposes. Solok is a district with the largest paddy field area in West Sumatra. Yet, the increase in population has resulted in a decrease in paddy fields every year. This study aimed to determine the model for changing the area of paddy fields for the 2000-2020 period and determine the direction of sustainable agricultural policies. In defining the paddy field change model, this research uses the input data from the interpretation of 2000 Landsat 5 imagery, 2010 Landsat 7 imagery, and 2020 Landsat Oli 8 imagery. The data were analyzed using a geographic information system (GIS). This research employed the Powersim Software with a system dynamics approach in projecting rice production and demand. This research used Interpretative Structural Modeling (ISM) analysis to determine the direction of sustainable food policy. The results showed that there had been a conversion of 13,801.6 hectares of paddy agricultural land into a built-up area in the 2000-2020 period in Solok District. In 2020, Solok District supplied 2,838 thousand tons of rice, while the demand for rice was 446.3 thousand tons. In the direction of the sustainable agriculture policy, there are three key sub-elements; tightening land use permits, establishing and implementing spatial planning regulations, and consistency in enforcing spatial planning violation laws.

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Introduction

Changes in land use, especially on agricultural land, are crucial things that drive the dynamic transformation between society and the environment. Land use change greatly affects food productivity, economic development, climate change, ecological systems, etc. The loss of agricultural land in areas with high productivity can trigger profound socio-economic impacts, such as the reduced supply of agricultural products, decreased living standards of the population, etc. (Azadi et al., 2018). Furthermore, inappropriate agricultural land reclamation in ecological areas can result in negative natural responses such as soil erosion, geological disasters, and so on (Keesstra et al., 2018).

Indonesia has the world's largest agricultural land area and is the third-largest rice producer after India and China (Fathonah, 2021). Apart from that, Indonesia is also responsible for about 8.5% of global rice production (Mahbubi, 2013; Mubarokah et al., 2020; Purwandoko et al., 2022). Rice is the primary source of food for more than half of the world's population (Krishnamoorthy et al., 2021). As a result, rice is a commodity that must be considered. Moreover, Nurmegawati et al. (2021) stated that the agricultural sector continues to have a significant impact on the national economy in the RPJMN 2020-2024. The agricultural sector's contribution can be seen in the provision of food, industrial raw materials, contributions to GDP, employment, and the primary source of household income for rural farmers (Zhang et al., 2019; Garo and Egbendewe, 2020).

Lands for regional development and agricultural land have some overlap (Liu et al., 2020). Several developed regions want to transfer quotas for agricultural land addition to relatively poor areas in exchange for economic compensation. More urban development space can be available in the region, but the decline in local food production and environmental uncertainty will be exacerbated (Huang et al., 2020). As a result, many agricultural lands in Indonesia have been converted into non-agricultural areas. The conversion of agricultural land to built-up land is a serious threat to national food security (Nurpita et al., 2017). Rapid urbanization and a slew of environmental safeguards have had a significant impact on the dynamics of changes in agricultural land use in the current period (Hasan et al., 2023). The negative impact of conversing the agricultural land has decreased national rice production by 1.08% in the last five years (Azadi et al., 2018). The area of paddy fields in Indonesia was 10.4 million ha, with a total production of 54.4 million tons. West Sumatra Province contributes 2.24% to national rice production (National BPS, 2021). The largest rice-producing area in West Sumatra is Solok District (Berd et al., 2022).

The conversion of agricultural land to non-agricultural land is usually the result of external and internal factors (Feng et al., 2020). Population trends, economic growth, and local government policies are examples of external factors. Internal factors include agricultural certificate perceptions, technical constraints on land characteristics, farming business scale, and farming profitability (Smith and Siciliano, 2015). Conversion of agricultural land is extremely concerning if it occurs in paddy agricultural land. This is because paddy fields are the most suitable land for maintaining food stability, so the function should not be changed to other land functions. The agricultural land conversion in West Sumatra in 2021 reduced rice production by 97.86 thousand tons (BPS West Sumatra, 2021).

This study aimed to determine the model of change in paddy fields for the 2000-2020 period and to develop sustainable agricultural policy directions in Solok District of West Sumatra Province.

Materials and Methods

Materials

The research was conducted in Solok District in West Sumatra Province, which has an area of 373,800 ha. Geographically, the location of Solok District is between 01^{0}20'27" and 01^{0}2'39" South Latitude and 100^{0}25'00" and 100^{0}33'43" East Longitude (Figure 1). The government center or district capital is in Arosuka. Solok District has 14 sub-districts and 74 nagaris. The data used in this research were Remote Sensing Data from Landsat 5 Image acquired in 2000, Landsat 7 ETM Image Acquired in 2010, and Landsat 8 OLI acquired in 2020 for land cover changes analysis. Statistical data from the Statistics Indonesia Agency were also used in this study to analyze the rice production and demands model and sustainable agriculture policy. Solok District has varied topography, such as plains, valleys, and 350 m to 1,500 m above sea-level hills. In Solok District, there are several large lakes, namely Lake Singkarak, Twin Lakes, and Lake Talang. In addition, the district has one active volcano, namely Mount Talang. Solok District is a wet area with an average rainfall of 2,242 mm/year and 184 rainy days. Demographically, Solok District had a population of 391,497 people in 2021, with a growth rate of 1.17% per year and a population density rate of 104 people/km^2. Approximately 58.44% of the population works in the agricultural sector. Changes to land cover were carried out at intervals of 20 years, namely from 2000 to 2020, by taking a range every five years; in 2000, 2010, and 2014. Administrative boundaries for the district area in this study used the 2016 administrative maps of a scale of 1: 25,000 from the Geospatial Information Agency. Land cover vector data was generated from the interpretation of raster data from Landsat 5 imagery in 2000, Landsat 7 ETM imagery in 2010, and Landsat Oli 8 imagery in 2020. Landsat imagery was used in this study because these images can record every 16 days at the same location. Thus, it increases the accuracy of image interpretation due to cloud disturbances during recording. In addition, the Landsat imagery used has a resolution of 30 meters and can produce land cover maps with a scale of 1: 50,000.

Methods

This study used digital image processing to generate spatio-temporal information on changes in land cover. Using Powersim Software, the data were then examined to model rice production and demand. To develop sustainable agricultural policy, the information obtained was further examined using the Interpretative Structural Modeling (ISM) technique.

Land cover changes analysis

Information on changes in land cover was obtained through spatio-temporal analysis of remote sensing data using Landsat imagery data. In remote sensing, Landsat image processing generally requires many rounds of preprocessing, including geometric and radiometric correction, to prepare the raw data for further analysis. Processing images were made using ENVI software. Geometric corrections were done to match the Landsat image to a known coordinate system in order to precisely estimate the location and extent of features within the image.

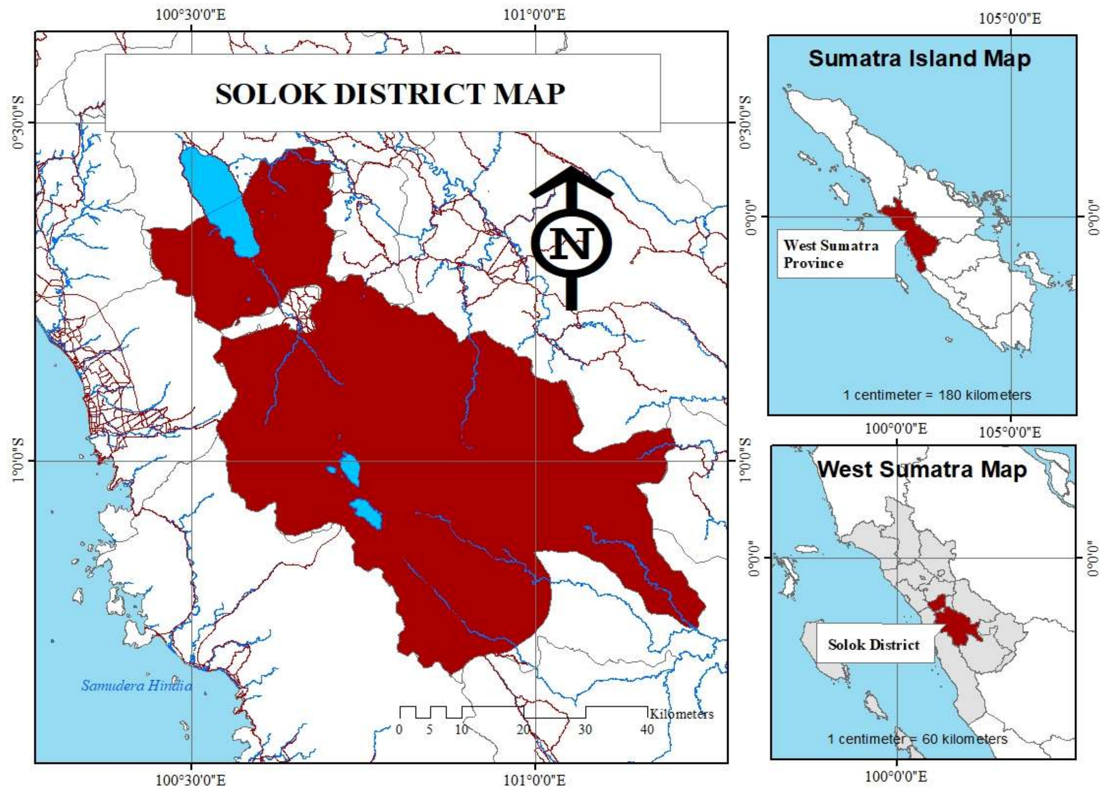

Figure 1. Research location map.

Next, the image is corrected radiometrically to correct visual distortions due to variations in air and other environmental conditions, as well as sensor noise and calibration mistakes. The data were then interpreted using supervised image processing techniques with the maximum likelihood method to produce land cover information for the years observed. The interpreted land cover consists of lake, forest, plantation, settlement, rice field, grass, and open ground.

Rice production and demands model

Processing tabular data acquired from the central statistics agency was used to analyze the production/supply model and demand for rice in the study area. The model is presented in the form of x and y curves that explain the link between rice production and demand. Furthermore, the curve is studied by paying attention to the curve's equilibrium and shift. In determining the production projection model and demand for rice, this research used the Powersim software. Rice is produced from the area of paddy fields multiplied by dry-milled grain (GKG) per hectare. In 2022, the Agricultural Research and Development Agency set GKG production at 54.42 tonnes per hectare. Meanwhile, the need for rice is obtained from the total population multiplied by the population consumption index per capita. BPS sets the national consumption index per capita at 114 kg or 312 g/day.

Analysis of sustainable agriculture policy

Sustainable agriculture policy was analyzed using Interpretative Structural Modeling (ISM). It is a popular system analysis tool that gives a systematic way to analyze complicated linkages and interactions between variables. The Interpretative Structural Modeling (ISM) analysis was used to pinpoint the course that sustainable food policy should take. The ISM method's fundamental tenet is the identification of system structures that offer high-value benefits in order to efficiently build the system and improve decision-making. The ISM technique's methodology includes creating a hierarchy and categorizing sub-elements (Marimin, 2004; Umar et al., 2017; Santoso et al., 2017; Umar and Dewata, 2019). The ISM method's steps are summarized as follows:

1) Identify elements and sub-elements with stakeholders using Focus Group Discussion (FGD).
2) Summarize the findings of the focus group and integrate them with the literature review to generate policy elements and sub-elements.
3) Establish the contextual relationship using the acronym VAXO, which can indicate any of the following:
    a. If eij = 1 and eji = 0, then V = the i^{th} sub-element is more important than the jth sub-element and not vice versa.

b. If eij = 0 and eji = 1, then A = the j[th] sub-element is more important than the ith sub-element and not vice versa.
c. X if eij = 1 and eji = 1; X = both sub-elements are equally important and interconnected.
d. If eij and eji are both 0, then O = the two sub-elements are unrelated.

4) Compile structural self-interaction matrix (SSIM)
5) Determine the reachability matrix based on SSIM and determine the transitivity matrix.
6) For each sub-element, compile the Driver Power Dependence (DPD) matrix. Each element is classified into four categories (Figure 2).
   a. Quadrant I: Unrelated (Autonomous) is made up of sub-elements with driver power values (DP) of 0.5 X and dependence values (D) of 0.5 X. Where X is the number of sub-elements contained within each element. Sub-elements in quadrant I are not related to/have little relationship with the system in general.
   b. Quadrant II: Dependent (Not Independent) is made up of sub-elements with a driver power value (DP) of 0.5 X and a dependence value (D) of 0.5 X. Where X is the number of sub-elements contained within each element. Quadrant II sub-elements are dependent on quadrant III elements.
   c. Quadrant III: Sub-elements that makeup linkage has driving power values (DP) and dependence values (D) that are both less than or equal to 0.5 X, where X represents how many sub-elements there are in each element. Because any action on one sub-element will have an impact on other sub-elements in quadrants II and IV, the sub-elements in quadrant III need to be carefully researched.
   d. Quadrant IV: Activator (Independent) is made up of sub-elements with driver power values (DP) and dependence values (D) that are both less than or equal to 0.5 X, where X is the number of sub-elements in each element.

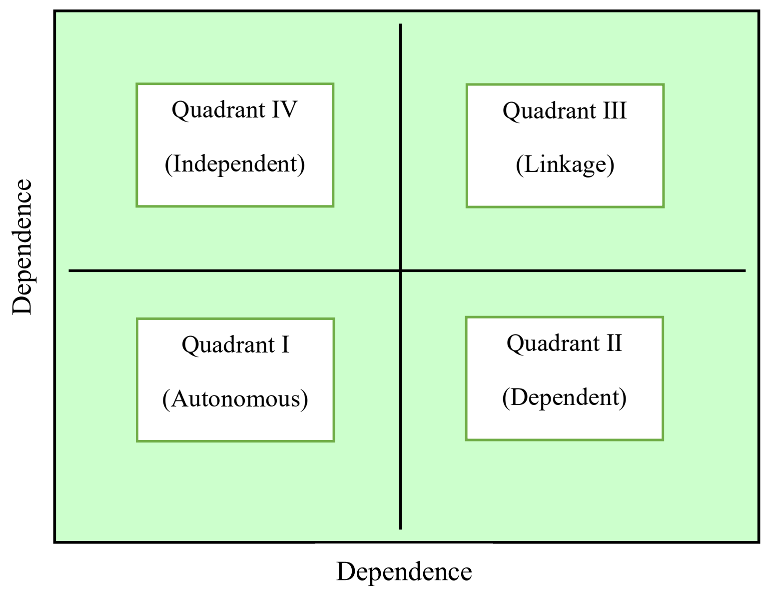

Figure 2. Driver power dependence quadrant matrix.

Experts in determining sustainable food policy directions were from relevant stakeholders, including the Center for Population and Environmental Research (PPKLH) UNP and the Department of the Environment (DLH) West Sumatra Province. Solok District Bappeda, Solok District Agriculture Office, Solok District Public Works Office, Community Leaders, Community Support Organizations (NGOs). The study enlisted the participation of 25 experts.

Results

The land cover of Solok District is changing all the time as a result of an increase in the population's need for both housing and agricultural land. Changes in land cover can be observed using Landsat ETM 5 imagery for 2000 compared to land cover in 2010 on Landsat ETM 7 imagery for 2010. The results of this image interpretation show that paddy fields in 2000 were about 65,924.5 hectares (17.6 %). However, in 2010 it decreased to 56,375.4 hectares (15.1%). Thus, Solok District, from 2000-2010, experienced a conversion of 9,549.1 hectares or 2.55% of paddy fields. Details information is presented in Figure 3. Furthermore, Table 1 shows a change in land cover in Solok District in the 2000-2010 period. Land covers that experienced a reduction in that period were forests, mixed gardens, paddy fields, shrubs, and open land. Meanwhile, the land that experienced an increase in area was residential areas, namely 27,418.2 hectares.

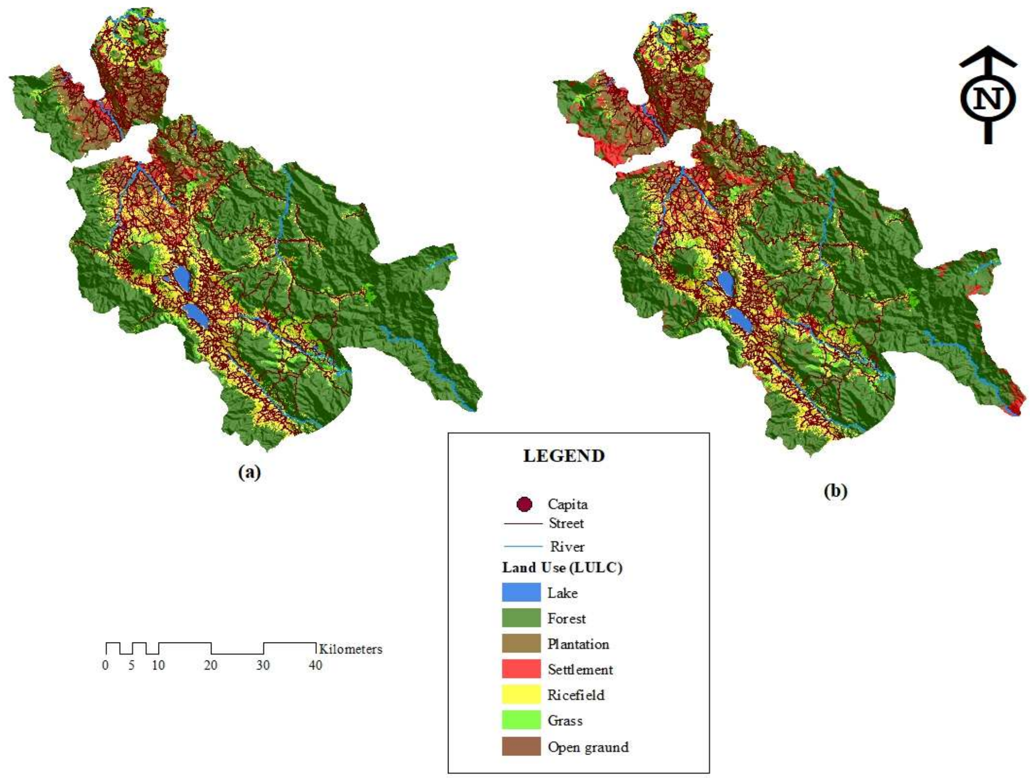

Figure 3. Land cover map of research locations in (a) 2000; (b) 2010.

Table 1. Land cover changes in 2000-2010 in Solok District.

Land Cover	**Period 2000-2010**		**Changes**	
	2000 (hectares)	**2010 (hectares)**	**hectares**	**Explanation**
Lake	2,972.4	2,972.4	0.0	No Changes
Forest	227,270.4	214,038.8	-13,231.6	Decrease
Plantation	40,469.5	39,461.5	-1,008.0	Decrease
Settlement	20,134.3	47,552.5	27,418.2	Increase
Rice Field	65,924.5	56,375.4	-9,549.1	Decrease
Grass	15,015.5	12,023.5	-2,992.0	Decrease
Open Ground	2,013.4	1,375.9	-637.5	Decrease
Total Area (ha)	**373,800**	**373,800**		

Sources: Landsat image interpretation of ETM 5 in 2000 and ETM 7 in 2010.

Figure 4 is a land cover map for the 2010-2020 period in Solok District resulting from the interpretation of Landsat ETM 7 imagery in 2010 and Landsat Oli 8 imagery in 2020. The analysis shows that the area of paddy fields in that period continued to decrease. In 2010, the paddy fields in the research area were 56,375.4 hectares. Yet in 2020, it has declined to 52,122.9 hectares. Therefore, Solok District lost 4,252.5 hectares of paddy fields in that period. In addition, Table 2 presents that the most land change occurred in residential areas. Table 3 shows that there has been a conversion of paddy agricultural land into built-up land covering an area of 13,801.6 hectares in Solok District during the 2000-2020 period. This condition will directly impact agricultural production and food security. Pham Thi et al. (2021) and Nguyen et al. (2019) stated that the conversion of agricultural land to non-agriculture was strongly influenced by population and economic growth. By having an increase in population, the need for land will increase. In addition, Chen et al. (2022) distinguished the factors causing the conversion of agricultural land into three, namely external, internal, and policy factors. External factors are caused by urban growth, population growth, and an increase in the population's economy. The internal factors of conversing agricultural land are the socio-economic conditions of the farmer's household and the area of arable land. Furthermore, policy factors are related to government regulations about the permits for land conversion.

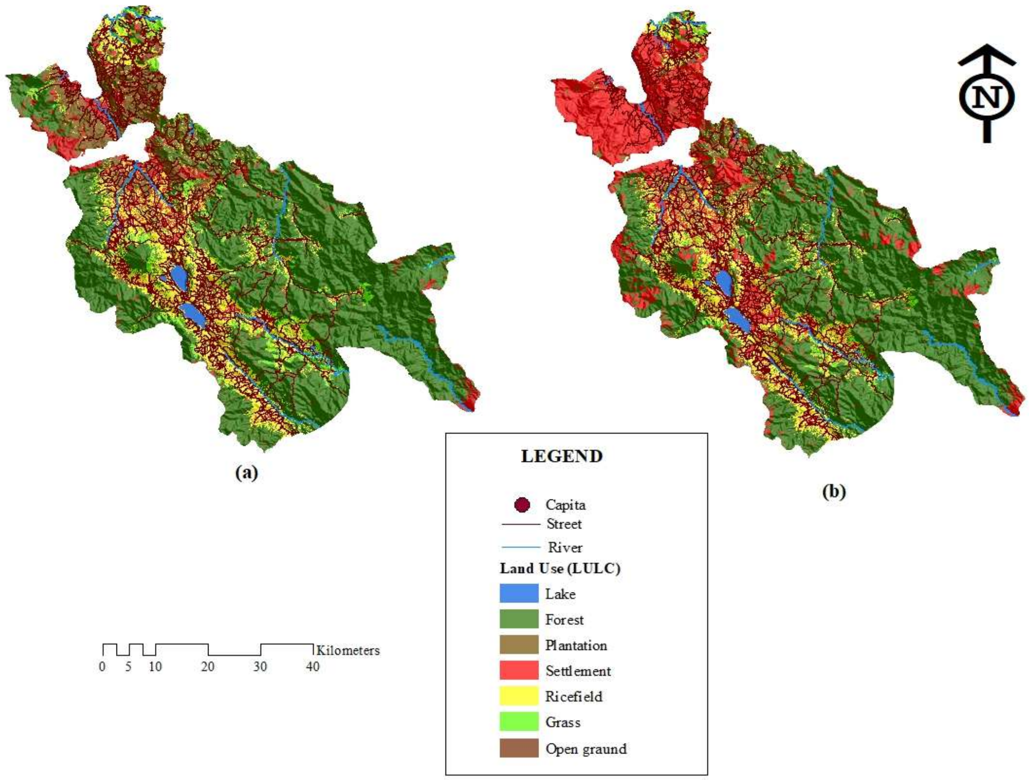

Figure 4. Land cover map of research location in (a) 2010; (b) 2020.

Table 2. Land cover for the 2010-2020 period in Solok District.

Land Cover	Period 2010-2020		Changes	
	2010 (hectares)	2020 (hectares)	hectares	Explanation
Lake	2,972.4	2,972.4	0.0	No Changes
Forest	214,038.8	201,260.6	-12,778.2	Decrease
Plantation	39,461.5	33,034.5	-6,427.0	Decrease
Settlement	47,552.5	73,154.4	25,601.9	Decrease
Rice Field	56,375.4	52,122.9	-4,252.5	Decrease
Grass	12,023.5	10,231.5	-1,792.0	Decrease
Open Ground	1,375.9	1,023.7	-352.2	Decrease
Total Area	**373,800**	**373,800**		

Sources: Interpretation of Landsat ETM 7 images in 2010 and OLI 8 in 2020.

Table 3. Changes in land cover in 2000, 2010, and 2020.

Land Cover	2000		2010		2020	
	hectares	%	hectares	%	hectares	%
Lake	2,972.4	0.8	2,972.4	0.8	2.972,4	0.8
Forest	227,270.4	60.8	214,038.8	57.3	201.260,6	53.8
Plantation	40,469.5	10.8	39,461.5	10.6	33.034,5	8.8
Settlement	20,134.3	5.4	47,552.5	12.7	73.154,4	19.6
Rice Field	65,92.5	17.6	56,375.4	15.1	52.122,9	13.9
Grass	15,015.5	4.0	12,023.5	3.2	10.231,5	2.7
Open Ground	2,013.4	0.5	1,375.9	0.4	1.023,7	0.3
Total Area	**373,800**	**100**	**373,800**	**100**	**373,800**	**100**

Sources: Interpretation of Landsat 5 imagery in 2000, Landsat ETM 7 imagery in 2010, and Landsat OLI 8 in 2020.

The food carrying capacity is significant for a region to maintain and create food sustainability (Sabila, 2020). The food carrying capacity can be determined by comparing the rice production and the demand in a region.

The carrying capacity value below 1 (one) indicates that an area is not self-sufficient in food (Mubarokah et al., 2020). Figure 5 is a projection graph between rice production and demand in Solok District. In 2020, with a land area of 52,122.9 hectares in the research area and milled grain (GKG) production of 54.42 t/ha, rice production in 2020 will be around 2,838 thousand tons. With a population of 391,497 people and a per capita consumption index of 114 kg, the need for rice is 446.3 tons. It means that the rice production in Solok District still exceeds the demand for rice. However, with the rate of conversion of paddy fields every year and a population growth of 1.17% /year, it can be projected that in 2040 the food-carrying capacity will experience inequality. It can be presented in Figure 6 as a graph of the carrying capacity of food in Solok District.

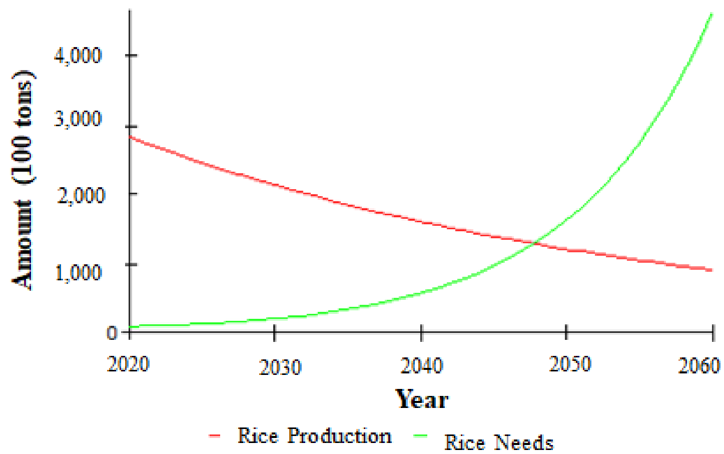

Figure 5. Projected relationship between rice production and rice demand in Solok District.

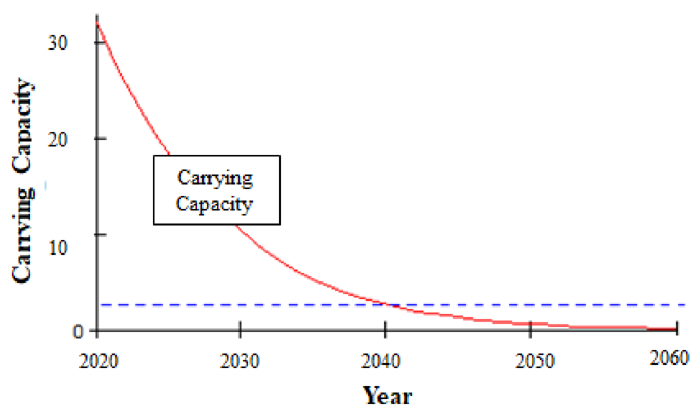

Figure 6. Graph of food carrying capacity in Solok District

To create food sustainability, it is necessary to formulate a sustainable agricultural policy directive. It is determined by the ISM method. Based on the Focus Group Discussion (FGD) with experts, 7 sub-elements of sustainable agricultural policy direction in Solok District could be identified.

E1 Providing incentives and disincentives
E2 Tighten permits for the function of rice field agricultural land
E3 Consolidating paddy fields
E4 Establishing and implementing regional regulations on spatial planning
E5 Building and rehabilitating irrigation network infrastructure
E6 Utilization of unused land to become productive agricultural land
E7 Consistency of law enforcement in spatial violations

Table 4 is the final result of the sub-element matrix of policy direction based on expert opinion through FGD.

These results indicate that two sub-elements have the highest drive power. They are (E4) establishing and implementing regional regulations on spatial planning, (E7) and consistency of law enforcement in violations of spatial planning. Other result shows three sub-elements that have a high dependency on other sub-elements, namely; a) provision of incentives and disincentives (E1); b) consolidate paddy fields (E3); and c) utilization of idle land to become productive agricultural land (E6).

Table 4. The sub-elements final matrix of sustainable agricultural policy directions.

Sub-Element	E1	E2	E3	E4	E5	E6	E7	Driver Power	Rank
E1	1	0	1	0	0	1	0	3	4
E2	1	1	1	0	1	1	0	5	2
E3	1	0	1	0	0	1	0	3	4
E4	1	1	1	1	1	1	1	7	1
E5	1	0	1	0	1	1	0	4	3
E6	1	0	1	0	0	1	0	3	4
E7	1	1	1	1	1	1	1	7	1
Dependence	7	3	7	2	4	7	2		
Level	1	3	1	4	2	1	4		

Source: ISM analysis (2022).

Figure 7 shows that the sub-element of making regional regulations on rice fields protection and being consistent in law enforcement has the highest rank. The two sub-elements' driver power is large but has little dependence on other sub-elements. In addition to these two sub-elements, the sub-element to tighten permits of conversing paddy fields is in the independent quadrant. It means that the three sub-elements are the key elements of sustainable agricultural policies in Solok District. Furthermore, Figure 8 explains four policy priority levels, sub-elements E4, E7, and E2 are the main priority sub-elements in creating sustainable agricultural policies. According to Satria et al. (2018), to create a sustainable agricultural land protection strategy for paddy fields. One of the efforts is cooperation between local government organizations (OPD) and legal certainty in taking action against spatial planning violations.

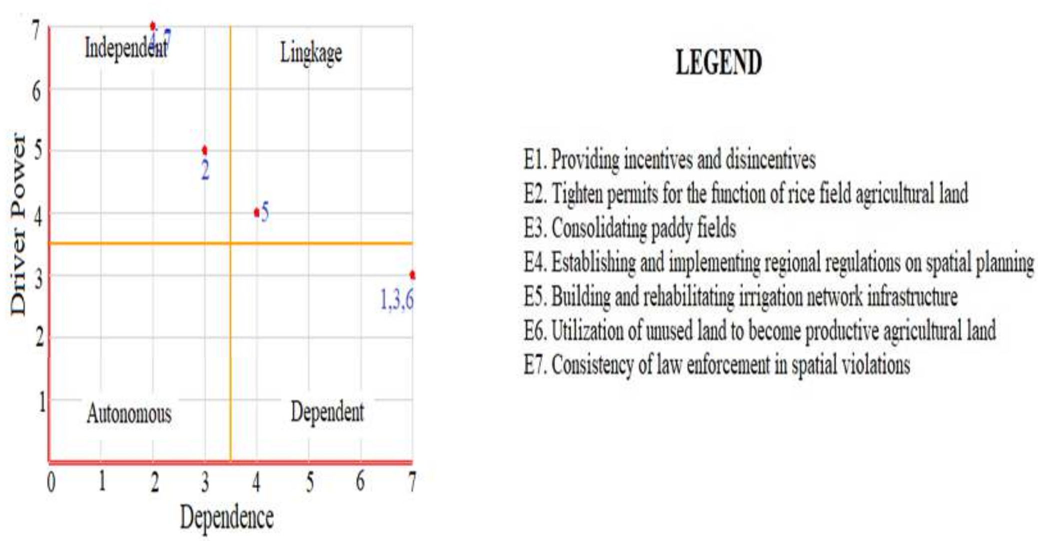

Figure 7. Diagram of sustainable agricultural policy directions sub-elements classification

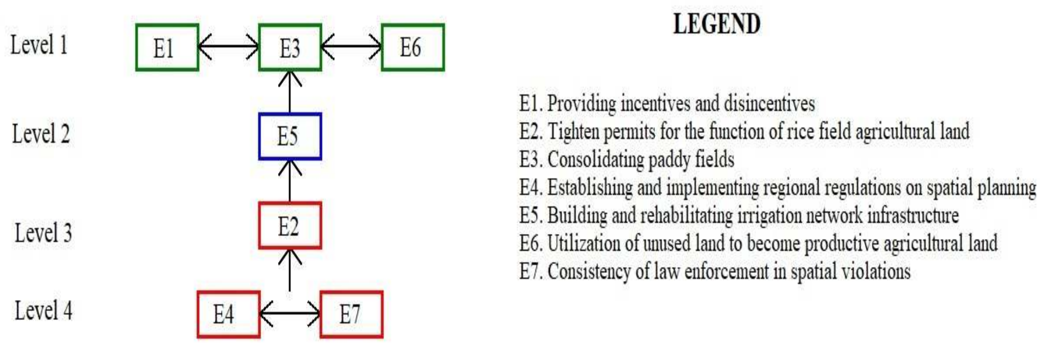

Figure 8. Model of the sub-elements hierarchical structure of the direction of sustainable agricultural policy.

Discussion

As expected, our findings showed that land cover continued to change as a result of an increase in population demand for both housing and agricultural land. Paddy field area significantly decreases every year, in line with previous studies which explain that agricultural land is decreasing in an area (Bless et al., 2018). The present study found that there has been a conversion of rice agricultural land into built-up land. This finding agreed with earlier research which stated that the conversion of agricultural land has been increasingly prevalent in recent years (Lark et al., 2015). With this land conversion, it will have a negative impact on production and food security (Smith et al., 2020).

Generally, the conversion of agricultural land is caused by population and economic growth (Marques et al., 2019). In addition, Chen et al. (2022) distinguished the factors causing the conversion of agricultural land into three, namely external, internal, and policy factors. External factors are caused by urban growth, population growth, and an increase in the population's economy. The internal factors of conversing agricultural land are the socio-economic conditions of the farmer's household and the area of arable land. Furthermore, policy factors are related to government regulations about the permits for land conversion.

Rice production in Solok Regency still exceeds the demand for rice. However, with the conversion rate of paddy fields every year and population growth of 1.17%/year, it can be projected that in 2040 the food-carrying capacity will experience inequality. This is consistent with research that says inequality will occur due to the significant rate of conversion of paddy fields and population growth (Rustiadi et al., 2021). From the results of ISM analysis and FGD with experts, 7 sub-elements of the direction of sustainable agricultural policy in Solok District were obtained. The most important sub-element is to make regional regulations regarding the protection of rice fields and be consistent in law. This has also been conveyed in previous research related to agricultural policies, most importantly regarding regional regulations regarding the protection of rice fields (Truelove et al., 2015). One of the efforts is cooperation between regional apparatus organizations and legal certainty in taking action against spatial planning violations, especially for paddy fields (Widowaty and Wahid, 2021)

Conclusion

In Solok District, there has been a change in the function of agricultural land to non-agriculture land. The changes happened from 2000-2020, with an area of 13,801.6 hectares. Landsat image interpretation results from 5 rice fields in 2000 with a total of 65,924.5 hectares area. Furthermore, in 2010 it decreased to 56,375.4 hectares from the interpretation of Landsat ETM 7 imagery. Finally, in 2020 from the Landsat Oli 8 imagery, the area of rice fields in Solok District remains at 52,122.9 hectares. With the area of rice fields owned by Solok District in 2020, rice production is 2,838 thousand tons, while the demand for rice is 446.3 thousand tons. It means that they can still be self-sufficient in food. To create sustainable agriculture in Solok District, there are three main priorities or key elements, namely: a) the establishment and implementation of spatial planning regulations; b) consistency of law enforcement in spatial planning violations; and c) tightening permits for the conversion of paddy fields.

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